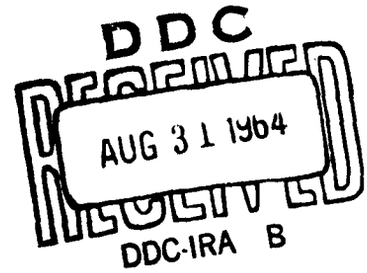
USNRDL-TR-766
21 July 1964

PHOTOGRAPHIC DETECTION OF FAST NEUTRONS: APPLICATION TO NEUTRON RADIOGRAPHY

by
E. Tochilin



U.S. NAVAL RADIOLOGICAL DEFENSE LABORATORY

SAN FRANCISCO · CALIFORNIA · 94135

RADIOLOGICAL PHYSICS BRANCH
E. Tochilin, Head

NUCLEONICS DIVISION
W. E. Kreger, Head

ADMINISTRATIVE INFORMATION

This report covers a portion of the work authorized by the Bureau of Ships, Subproject SF 011 05 11, Task 0503. Details are found in the U. S. Naval Radiological Defense Laboratory's Technical Program Summary for Fiscal Years 1964-1968, USNRDL-PR-53, of 1 April 1964, under Program D-1, Problem 4.

DDC AVAILABILITY NOTICE

Qualified requesters may obtain copies of this report from DDC.

Eugene P. Cooper

Eugene P. Cooper
Scientific Director

D. C. Campbell, CAPT USN
Commanding Officer and Director

12ND NRDL P1 (9/63)

ABSTRACT

The response of photographic emulsions to fast neutrons has been studied by direct measurements at two neutron energies and by exposure to high-energy charged particles. Dose response was significantly less for neutrons than for gamma rays and decreased progressively with decreasing neutron energy. Increased neutron sensitivity was obtained by use of organic scintillators as intensifying screens in conjunction with film. Neutron radiographs at two different energies were taken with step wedges made of Al, Cu, Pb and plastic. Radiographs were taken behind 2, 4, 6 and 8 inches of lead. Loss of photographic resolution from gamma rays produced in the test sample and by thermal neutron interactions is discussed.

SUMMARY

The purpose of this experiment was to investigate photographic detection methods applicable for fast neutron radiography. The neutron response of different photographic emulsions was investigated. Improved neutron response was obtained when the films were exposed in contact with organic phosphor materials. Test samples of Pb, Al, Cu and plastic were radiographed with fast neutrons. Lack of discrimination between different materials exposed to neutrons limits use of the technique to reasonably large thicknesses of homogeneous materials. It is concluded that fast neutron radiography offers no advantage over conventional radiographic methods.

INTRODUCTION

The neutron sensitivity of photographic emulsions has been the subject of many investigations.[1,2,3] Film has wide application as a personnel monitor for radiation workers. Under certain exposure conditions where combined neutron and gamma-ray exposures may be received, interpretation of film blackening is possible only if the neutron response of film is known. Photographic dosimeters have also been widely used to measure the initial gamma radiation at nuclear weapon tests. Here again a significant portion of the initial radiation dose may be from fission neutrons, depending on the type of weapon and distance from the source.

Fast neutrons, which are the subject of this report, are generally considered to have energies from 10 keV to about 10 MeV. The neutron response of film may be directly determined by exposure to a wide range of neutron energies. Using this approach, Smith and Benck have determined the thermal and fast neutron response of eight dosimeter films for neutron energies up to 14 MeV.[1] An alternate method to estimate the neutron sensitivity of film involves direct exposures to charged particles, since film blackening is primarily due to recoil protons produced by neutron interactions in the film.

This paper begins with a discussion on the neutron response of different films, primarily in relation to their gamma-ray sensitivity. Because of the relatively high gamma background normally associated with neutrons, this becomes an important consideration for evaluating the practicality of fast neutron radiography. Techniques for enhancing film blackening by means of intensifying screens are next covered. Fast neutron interactions in material and the subsequent production of gamma rays are then discussed. The concluding section describes experimental work in fast neutron radiography done at the University of California 60-in. cyclotron using two different neutron energies.

Throughout this paper it will become apparent that there are many limitations to the use of fast neutrons for radiographic purposes. In this sense one may be left with the impression that the negative aspects so override any positive features that this is essentially a negative

report. Nevertheless, the information will have served its purpose if it gives future investigators a clearer picture of the difficulties involved, and, in this way, suggest other methods of applying fast neutrons to nondestructive testing.

FILM RESPONSE TO CHARGED PARTICLES

The author has made studies of film response over a broad range of charged particle energies using 340-MeV protons, 190-MeV deuterons, 900- and 380-MeV alpha particles produced by the University of California 184-in. cyclotron.[3] In addition, film response to 50-MeV protons from the U. C. 88-in. cyclotron have recently been made. The films investigated during this study are given in Table 1.

The passage of an ionizing particle through material is characterized by its energy loss per unit length of path. It may be defined in several ways, namely as rate of energy loss dE/dx, linear energy transfer (LET) or stopping power. The rate of energy loss depends upon the charge and velocity of the incident particle and on the nature of the stopping material. For example, a proton and electron traveling at the same velocity will have the same dE/dx. A deuteron is a hydrogen isotope of mass 2 and has the same dE/dx as a proton with one-half the deuteron energy. For multiply charged particle dE/dx at any given velocity increases approximately as the square of the charge.

Figure 1 shows the results of measurements made with the 190-MeV deuteron beam using Kodak Translite film and Kodak Type NTB stripping film. The latter film is a thin nuclear emulsion on a cellulose acetate backing which is used in autoradioautography. Physical properties of the particle beams from the 184-in. cyclotron have been reported by Tobias, et al.[4] Progressively increasing values of relative ionization were obtained by passing the beam through various thicknesses of plastic absorbers. The relative ionization curve was obtained by comparing the measurements of two identical ionization chambers, with one placed directly ahead of and the other directly behind a given thickness of absorber. The film response curves were similarly obtained by comparing the recorded dose on the front film to that at any absorber depth. In this case the relative dose response curve for the NTB nuclear emulsion is observed to follow the relative ionization curve.

Table 1

PHOTOGRAPHIC EMULSIONS EVALUATED FOR CHARGED PARTICLE SENSITIVITY

Manufacturer	Film	Type	Particle Beam
Kodak	Translite	Positive Transparency	a, b
	5302	Positive Film	a, b
	KK	X Ray	c
	NTA	Nuclear Emulsion	a, b
	NTB	Nuclear Emulsion	a, b
DuPont	606	Positive Film	c
	502	X Ray	c
Ilford	G-5	Nuclear Emulsion	c

a. 190-MeV deuterons

b. 380-MeV α-particles

c. 900-MeV α-particles

This indicates that the dosage sensitivity, the blackening produced per unit ionization, remains essentially constant over the energy range covered. The lower curve showing particle flux was determined by Faraday cage measurements. It is of interest to observe that the Translite film behaves very much like a particle flux detector or as a Geiger-Mueller counter rather than as an ionization chamber. This is essentially so for all conventional X-ray emulsions, and for all but the most insensitive personnel monitoring films. Finally, the curve giving the rate of energy loss per particle dE/dx in plastic was obtained by dividing the relative ionization curve by the relative particle flux curve. The rate of energy loss for deuterons at the front surface of the Lucite was 0.8 keV/μ, as taken from the range-energy curves of Rich and Madey.[5]

The information from Fig. 1 combined with similar measurements made with other particles allowed the relative dosage sensitivity of film to be evaluated over all values of dE/dx pertinent to neutron and gamma-ray exposures. Dosage sensitivity is defined here as the equivalent dose recorded by a given film determined from a characteristic curve obtained with Co^{60} gamma rays, divided by the charged particle dose as determined by ionization chamber measurements. Such a curve is plotted in Fig. 2. Electron and proton energies corresponding to a given dE/dx have also been included on the abscissa.

The significant points about Fig. 2 regarding neutron exposures are:

(1) Proton-sensitive nuclear emulsions (such as NTB) will measure proton dose down to energies of about 40 MeV with about the same efficiency as for Co^{60} gamma rays. Dosage sensitivity then decreases rapidly for lower proton energies.

(2) X-ray and dosimeter films as illustrated by Kodak Translite and Type KK emulsions behave essentially as particle flux detectors. Dosage sensitivity decreases reciprocally with increasing dE/dx over most of the region. For proton energies below 5 MeV, the region of interest for most neutron exposures, the dosage sensitivity has decreased to about 10 percent or less. This means that a 10 percent gamma-ray component in such neutron beam would produce the same film response as the resulting recoil protons.

(3) Differences in charged particle response between coarse grained emulsions of maximum sensitivity and of fine grained X-ray emulsions are not significant when compared with differences that can be obtained with proton-sensitive nuclear emulsions. However, Smith and Benck found that for actual neutron exposures, film sensitivity

decreases with increasing grain size.[1]

INTENSIFYING SCREENS

The low sensitivity of X-ray film to fast neutrons raises the question if intensifying screens could be used advantageously as with X rays or gamma rays. The intensifier mechanism may be defined as a transfer device which will absorb the incoming energy at high efficiency, convert it in some useful manner, and transfer the converted energy to the film with high efficiency. The energy can be in the form of low-energy X rays, UV or visible light, or charged particles. Conventional X-ray screens used in industrial radiography are mostly of the calcium tungstate type, where absorbed X-ray energy is converted into light. The high atomic number of the material allows the screens to absorb as much as 50 percent of the incident radiation at X-ray energies of 100 kv or less. Absorption decreases rapidly at higher energies where the Compton absorption process rather than the photoelectric effect predominates.

Metal screens are used extensively at the higher kilovoltages. The intensifying action results largely from secondary electrons generated by the X rays which then penetrate the emulsion placed in direct contact with the screen. Both of these methods can be directly applied to fast neutron radiography.

The most efficient screen material for fast neutrons is one with high hydrogen content. Plastic scintillators such as p-terphenyl or organic crystals such as anthracene or stilbene are suitable materials.[7] The plastic materials are preferable because they are more readily available in sheet form. Because of the relatively large mean free path of neutrons, the scintillator must be quite thick to achieve any significant increase in sensitivity. Since the light transmitting properties of plastic scintillants is excellent, this requirement presents no problem. Finite screen thickness will, however, affect resolution or sharpness of image.

The scintillation response of organic crystals has been investigated over a wide range of dE/dx. The scintillation response curve for anthracene, shown in Fig. 3, is taken from the theoretical model developed by Birks on the basis of earlier experimental data.[8] The

response curve is similar for organic crystals, plastics and liquid scintillators. Relative scintillation efficiency is defined as the light output produced per MeV of a given particle energy to that produced by a 1-MeV electron. It is observed that the relative response decreases progressively with increasing dE/dx in somewhat the same manner as for photographic emulsions. The light efficiency for a 5-MeV proton is 0.4 that of a 5-MeV electron. Although the relative neutron to gamma-ray efficiency is better than for X-ray film, the response is still significantly in favor of gamma rays.

Calcium tungstate screens or other inorganic phosphors may also be used in direct contact with photographic emulsions. Because the energy loss per neutron interaction with nonhydrogenous material is small, and the light output from the resulting heavy recoil particles is extremely inefficient (high dE/dx), one must rely on secondary processes to produce recoil protons that will interact with the screen material.

X-ray emulsions generally contain from 10 to 20 percent silver halide by volume with the higher concentrations reserved for the coarser grained sensitive emulsions. The remaining 80 to 90 percent consists of gelatin, a compound in which roughly one-half the atoms are hydrogen, its exact hydrogen content depending on moisture content as determined by the relative humidity. Cellulose acetate which is commonly used as a backing material for the emulsion has approximately the same hydrogen concentration. Thus, film in contact with an inorganic phosphor such as calcium tungstate or zinc sulfide would serve as a proton radiator during neutron irradiation. Luminescence in the phosphor is produced by the recoil protons penetrating the screen. Another method of achieving the same result is by the use of organic binders or cements in the manufacture of fluorescent screens or by a transparent plastic cover of enhanced hydrogen content.

Another relative advantage offered by an inorganic crystal would be in its improved dE/dx response for protons over that of an organic phosphor. While little information is available on the response of conventional radiographic screens, considerable data exist on the dE/dx response of alkali halide scintillants. Figure 3 shows the response of NaI(Tl) crystal containing 0.2 percent of thallium activator.[9] The response curve is typical for the entire class of alkali halide crystals. The main point of interest is that scintillation efficiency increases with increasing dE/dx and reaches a maximum value for protons in the range from 10 - 50 MeV. Scintillation efficiency for protons remains above that of high speed electrons for proton energies down to 1 MeV. Beyond this point there is a rapid decrease in dE/dx response.

The extent to which this improved response can be utilized depends on the geometrical relationship between the radiator and phosphor. When the radiator is placed directly in contact with the phosphor, the over-all sensitivity will be determined by the thickness of phosphor layer. The range of a 10-MeV proton in an inorganic phosphor is in the order of 0.2 gm/cm^2. For a material of density 2, a 10-MeV proton will penetrate to a depth of 1 mm. If a phosphor 0.5 mm thick is used and we assume that proton range is proportional to energy, then protons with energies of 5 MeV and greater can penetrate the phosphor. Light output will be proportional to the total energy deposited by each proton traversing the phosphor. Protons with lower energies will be stopped in the phosphor and can therefore interact with a limited fraction of the total phosphor volume. Thus, all protons with ranges less than the phosphor thickness will be detected with reduced efficiency. This means that the radiator-phosphor combination will be more efficient for high-energy neutrons unless the phosphor is kept extremely thin -- which can only be done at the expense of reduced sensitivity.

In summary, organic screens offer the advantage of maximum energy absorbed per neutron interaction, significantly in excess to that from any accompanying high-energy gamma rays. Conversely, because of their unfavorable dE/dx response, the light output per unit energy deposited in the material can be as small as 10 percent for 1-MeV neutrons as for gamma rays. The dE/dx response of certain inorganic phosphors allows protons to be detected with greater sensitivity than electrons. Since they are relatively insensitive to neutrons, a proton radiator must be used. Sensitivity is limited by the range of the recoil protons penetrating the phosphor and decreases markedly for lower neutron energies. For either type of intensifying screen, it appears that the relative neutron response will be significantly less than gamma-ray response.

GAMMA RAYS FROM NEUTRON INTERACTIONS

In evaluating the neutron response of film and intensifying screens, much emphasis has been placed on the greater efficiency of gamma rays. This was done because any radiographs obtained with fast neutrons will be made in the presence of a gamma-ray background. Most neutron beams are to some degree contaminated with gamma rays. These can originate

as a result of the target atoms left in an excited state during the charged particle interactions leading to neutron production. In this case, both neutrons and gamma rays originate at the target. When fast neutrons are produced by a cyclotron, a large circulating current is generated within the dees, only a part of which may be deflected to an external target. Some particles lost from the circulating beam strike the dees or deflector plate to produce gamma rays. In this case, the gamma-ray source is not well defined and considerable shielding may be required to eliminate its presence.

However, even relatively clean beams will produce secondary gamma rays in passing through a material. In the neutron energy range above 3 MeV, gamma rays are produced by inelastic scattering. This is the main process by which high-energy neutrons lose energy in heavy materials. Hydrogen is the only element that exhibits no inelastic scattering. Inelastic scattering occurs when a neutron enters a nucleus and emerges at a lower energy than at which it entered. One or more gamma rays equal in energy to the difference between the original and emitted neutron are emitted in the process.

For neutron energies below 3 Mev, scattering is primarily an elastic process where the sum of the kinetic energies of all particles in the system remains constant. The neutron collides with a nucleus, is scattered and loses energy which appears as kinetic energy of the recoil nucleus. The average neutron energy loss per collision is one-half for a hydrogen atom and becomes progressively less with increasing mass of scatterer. After many scattering events the neutron becomes thermalized. Thermal neutrons are readily captured by a target nucleus to form a compound nucleus which under certain conditions may emit gamma rays. Thermalization occurs most rapidly in hydrogenous material where subsequent capture of the thermal neutron capture results in the production of a 2.2-MeV gamma-ray photon.

The buildup of thermal neutrons and 2.2-MeV gamma rays in water for two cyclotron neutron spectra are shown in Figs. 4 and 5. Neutrons were produced at the University of California 60-in. cyclotron by bombarding a thick Be target with 12-MeV protons and with 20-MeV deuterons[10] (for the neutron radiographs to be described later the deuteron energy was increased to 24 MeV). Proton bombardment produced a neutron spectrum similar to that of fission neutrons with an average energy of approximately 1 MeV. Deuteron bombardment produced a continuous neutron spectrum with a population maximum at 9 MeV and a measurable maximum energy of 25 MeV. The penetrating properties are similar to that from 14-MeV neutrons produced with low-energy accelerators utilizing the $H^3(d,n)He^4$ reaction.

In Fig. 4 (fission type spectrum) one notices a rapid buildup of thermal neutrons to a depth of 2 in. at which point they approach an equilibrium with the fast neutrons from which they originate. The gamma-ray dose is, in turn, the result of thermal neutron capture in hydrogen followed by emission of a 2.2-MeV gamma-ray photon. Since these gamma rays are more penetrating in water than the fast neutrons they eventually become the prime source of radiation. It is apparent that neutron radiography of thick sections of organic material becomes completely impractical at these energies.

In the case of the deuteron produced neutron spectrum a similar rapid buildup of thermal neutrons occurs, as shown in Fig. 5. At these energies the fast neutrons are more readily transmitted in water. As a result the gamma-ray dose does not exceed 15 percent of the neutron dose at any point. It should be emphasized that these secondary gamma rays will act as a diffuse scattered source of radiation against which it is extremely difficult to shield.

The buildup of thermal neutrons and gamma rays takes place more slowly and to a lesser degree in nonhydrogenous material. In high-density material, such as lead, the resultant gamma rays are readily absorbed and their attenuation in the medium will always be greater than that of the fast neutrons. Nevertheless, since they represent an end product of the degraded neutron beam they cannot be entirely eliminated.

The presence of thermal neutrons introduces a further complication which will be discussed only briefly. Thermal neutrons blacken photographic emulsions primarily by the production of radioactive silver within the emulsion. The thermal neutron sensitivity is such that 10^{10} n/cm^2 will produce approximately the same density as 1 r of Co^{60} radiation.[1] Thus any significant thermal neutron component will produce still another background effect.

EXPERIMENTAL FAST NEUTRON RADIOGRAPHY

Since the usefulness of any radiographic technique depends on the ability of a given material to absorb the incident radiation, one might inquire to what extent this is possible with fast neutrons. The advantages of thermal neutron sources have been reviewed by Berger and others who have demonstrated specific ways in which this form of neutron

radiography may be utilized.[12,13,14] The exceedingly strong absorption characteristics of many light elements such as hydrogen, lithium and boron allow complete absorption of thermal neutrons in small amounts of material. The effect is comparable to radiographs obtained of high-density materials such as lead or gold with low-energy X rays.

On the other hand, the absorption characteristics of fast neutrons do not differ markedly above neutron energies of 100 kv. This means that strong differential effects would not be expected at different neutron energies. Hydrogen is one exception as demonstrated by the increased absorption in water for average neutron energies of about 1 MeV (Fig. 4) compared to 10 MeV (Fig. 5).

Even under most favorable conditions as represented by the attenuation of 1-MeV fast neutrons in water, the photographic image would be little different than that obtained with a plastic sample irradiated with 100 kv X rays. Therefore the degree of detail one can obtain from a neutron radiograph will be extremely limited when compared with gamma rays.

Experimental fast neutron radiographs were made at the 60-in. cyclotron using the two previously described neutron energies. The gamma-ray background with the 12-MeV protons and 24-MeV deuteron beams was 5 percent and 2 percent of the neutron dose respectively.

Radiographs were taken of 3 in. by 3-1/2 in. by 1 in. blocks of plastics, Al, Cu and Pb in which various sized holes of 1/8, 3/8, 5/8 and 7/8 in depth were drilled. Kodak Type K, DuPont 502, and Kodak Type NTA nuclear emulsions, 25 microns thick, were used. Runs were also made with DuPont 502 film and front screens of a plastic fluor (p-terphenyl) described by Wouters.[11] The phosphors were prepared in the form of 1-in. diameter disks, 3/16 in. thick. All exposures were made at a distance of 20 in. from the target. Test specimens were located within a lead cave with 4-in. walls in order to minimize any source of radiation not originating at the target. Exposure times averaged 0.5 μa-hr with the 12-MeV proton beam and 0.04 μa-hr with the 24-MeV deuteron beam for Kodak Type K and DuPont Type 502 films. These times were reduced approximately twentyfold when front plastic screens were used.

The test blocks were first exposed intact and then with varying thicknesses of lead absorbers placed in front of the blocks. Lead absorbers were used to minimize buildup of any gamma rays that might have been produced by thermal neutron capture or inelastic scattering.

Figure 6 shows a neutron radiograph with 12-MeV protons of the Pb block taken with bare DuPont 502 film and with the front plastic screens. The bright ring around the individual 1-in. phosphor disks is an intensifying effect produced by light emitted at the edges. The black specks are from dust particles. Figure 7 is a similar radiograph taken with a 2-in. Pb shield placed in front of the Pb block. At this point, holes in the Pb block are barely resolvable. No marked difference is observed between the bare film and plastic screens. Exposures were also made with 4-in., 6-in., and 8-in. Pb absorbers. At 4 in. only the largest hole could be distinguished on the bare film while nothing could be detected behind the plastic screens.

Several runs made with a 2-in. plastic absorber placed ahead of the Pb block gave similarly negative results. Virtually the same results were obtained when neutron exposures were made with the 24-MeV deuteron beam, except that the bare film showed slightly more detail with the 4-in. Pb absorber. Once again, nothing could be detected behind the 6-in. and 8-in. Pb absorbers. A limited number of radiographs made with NTA nuclear emulsions gave approximately the same results. Exposure times of from 20-50 times longer were required to obtain the same photographic density as with the X-ray emulsions.

Figure 8 shows a Co^{60} radiograph of the same Pb block. In this case the contrast is less pronounced with the plastic absorbers than with the bare film. A Co^{60} radiograph of the plastic block looked very much like the neutron radiograph of the plastic block shown in Fig. 6.

Neutron radiographs taken with the plastic Al and Cu blocks were inferior to those taken with Pb. A significantly higher over-all background was observed with all three materials. With a 2-in. Pb absorber ahead of the blocks the background had increased to the point where positive identification of any but the most obvious holes was virtually impossible. It therefore appears that while fast neutron radiographs of limited resolution can be made with relatively thin sections of material, neutron scattering plus the buildup of gamma rays from thermal neutrons precludes the technique from being used with material thicker than several inches.

One further question that arises is the degree to which the observed radiographs are truly neutron exposures. For the two types of film exposures made with the fission type neutron spectrum (bare film and film plus phosphor) there is a significant enough disparity in neutron sensitivity to expect some differences in photographic resolution. If one assumes an average neutron energy of 1 MeV, then from the data of Smith and Benck 190 neutron rad would be required to produce the same density in DuPont Type 502 film as 1 rad of Co^{60} gamma rays.[1] Thus with

a 5 percent gamma-ray dose as background one would expect film blackening for gamma rays to be some tenfold greater than from neutrons. For the 502 film exposed with front plastic screens the neutron to gamma-ray sensitivity from Fig. 3 would be the order of 0.1. Film blackening from neutron exposure should now be approximately twice that from the gamma-ray background. However, the only obvious difference in resolution obtained for the two types of exposure occurred with the addition of a 4-in. Pb absorber. In this case, detail was observed with the bare 502 film where nothing could be detected with the front plastic screens. This suggests that the scattering of neutrons in the Pb absorber completely obliterated any neutron pattern whereas the more directional initial gamma rays were probably responsible for whatever detail could be seen with the bare film. The direct effect of gamma rays becomes less pronounced as one goes to higher energy neutrons.

SUMMARY AND CONCLUSIONS

1. Because of their inherently low neutron sensitivity, photographic detectors are generally not capable of discriminating against the gamma-ray background associated with fast neutron beams.

2. Of the photographic detection methods presently available, organic scintillants offer the best promise as photographic intensifying screens for fast neutron radiography.

3. Fast neutron radiography does not offer the discriminating capability between different materials that one can obtain with X rays, gamma rays, or thermal neutrons. This limits its application to the radiographic inspection of reasonably large thicknesses of homogeneous materials.

4. Considering the fast neutron radiography of light materials, the buildup of thermal neutrons and gamma rays within the inspection material for lower energy fast neutrons (Fig. 4) would introduce a high background for all but very thin inspection materials. For higher energy fast neutrons this background becomes less of a problem (Fig. 5), but is still significant.

5. Considering the fast neutron radiography of heavier materials, the decreased moderation of fast neutrons and increased attenuation of

gamma rays both tend to reduce the radiation background problem. However, neutron scattering within large masses of inspection material becomes a limiting factor in determining resolution capability.

Because of these limitations one is forced to conclude that fast neutron radiography with currently available photographic detection techniques offers no improvement over conventional radiographic methods. It further appears that there is no physical basis for expecting to find unique radiographic conditions where the supplemental use of fast neutrons could in any way improve existing techniques.

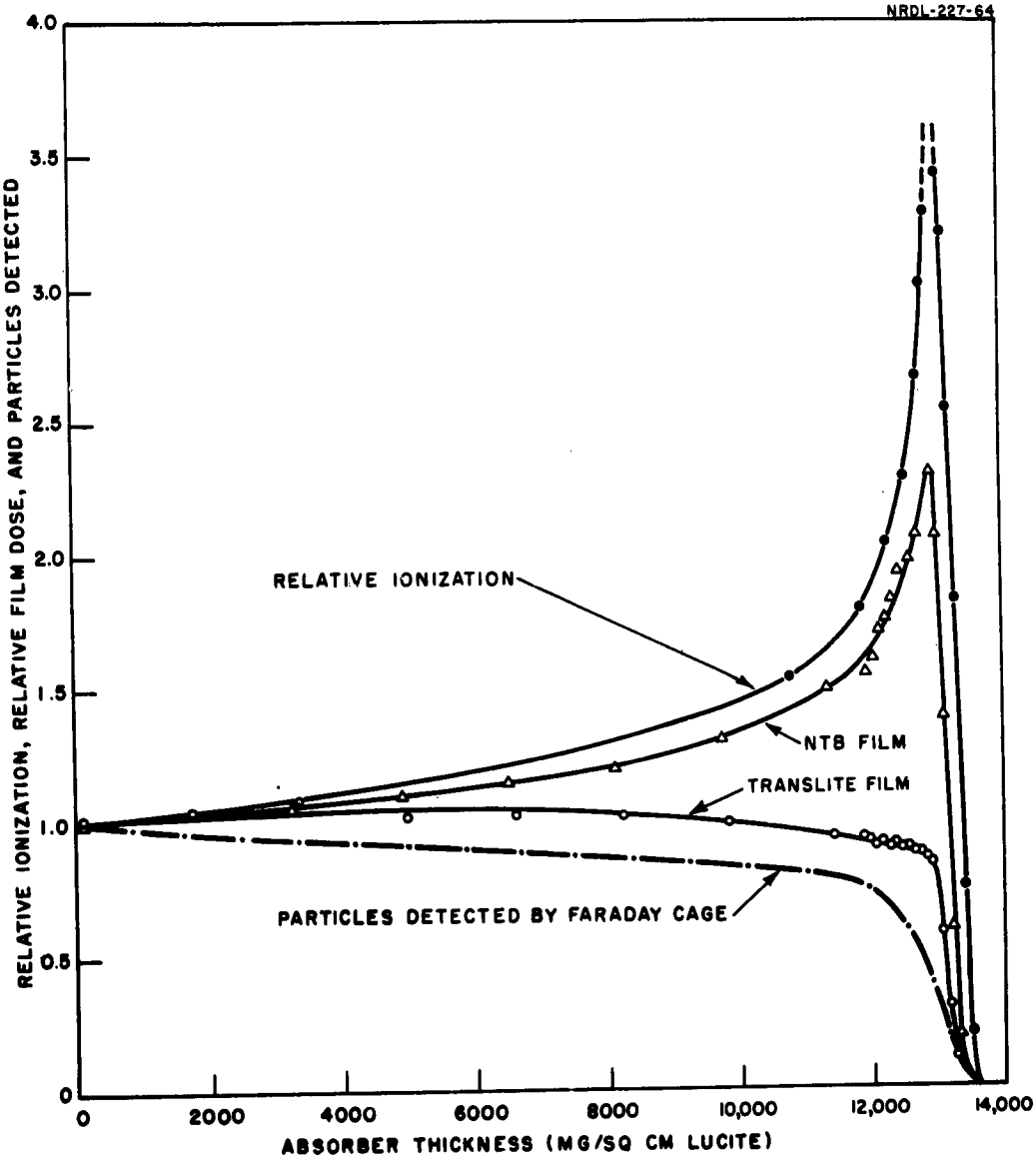


Fig. 1 Relative ionization and film response for 190-MeV deuterons.

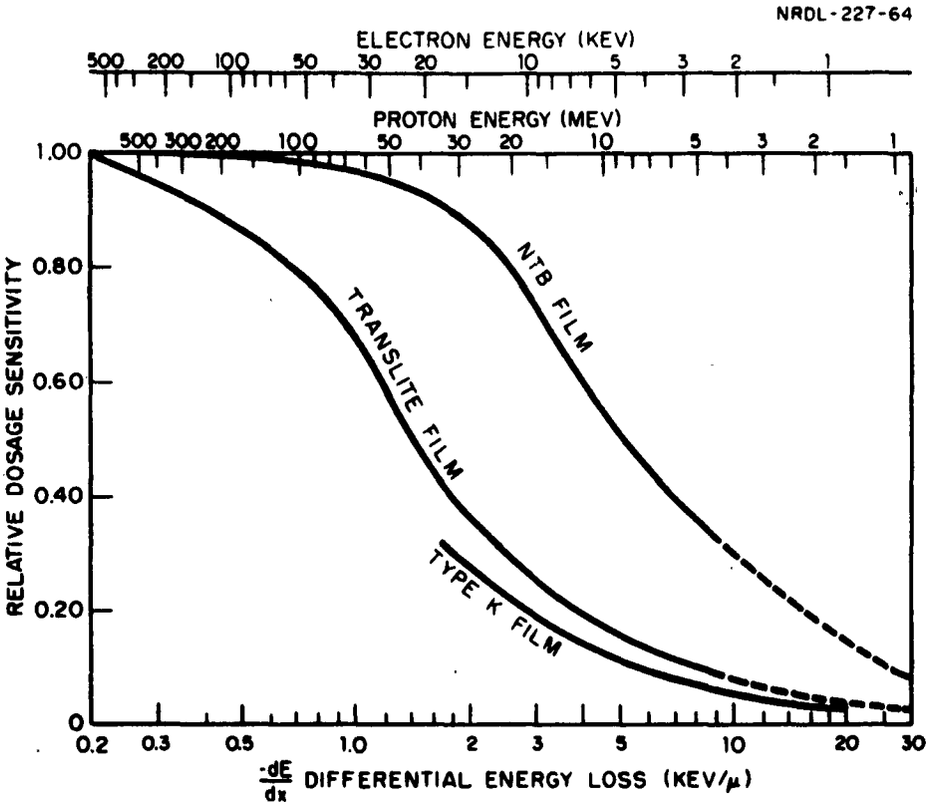


Fig. 2 Relative dosage sensitivity of film versus dE/dx.

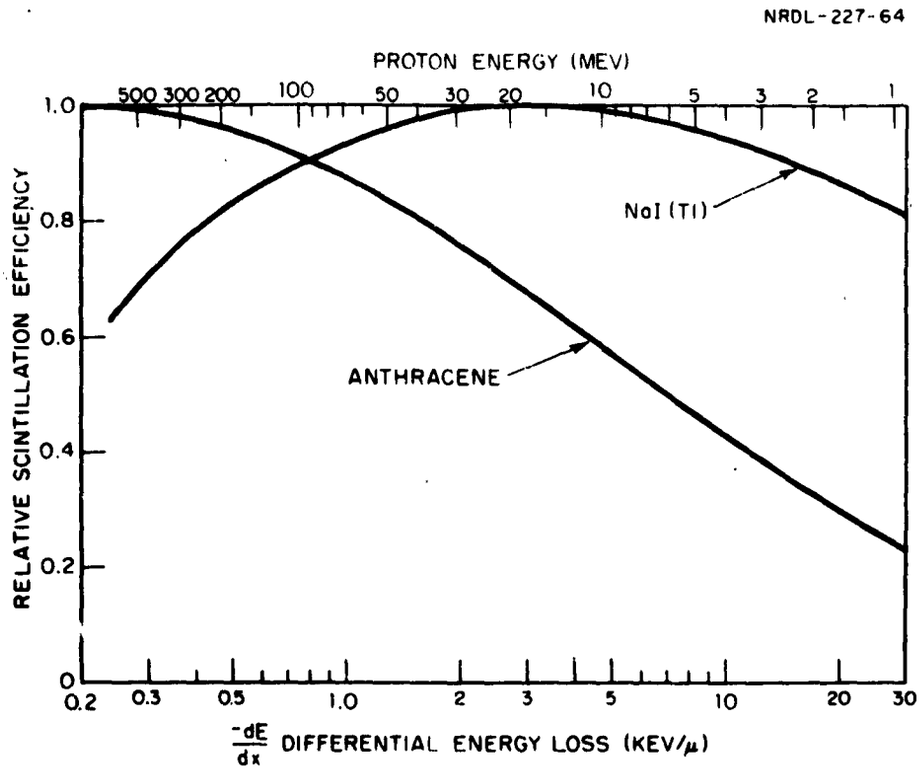


Fig. 3 Scintillation efficiency of organic and inorganic phosphors versus dE/dx.

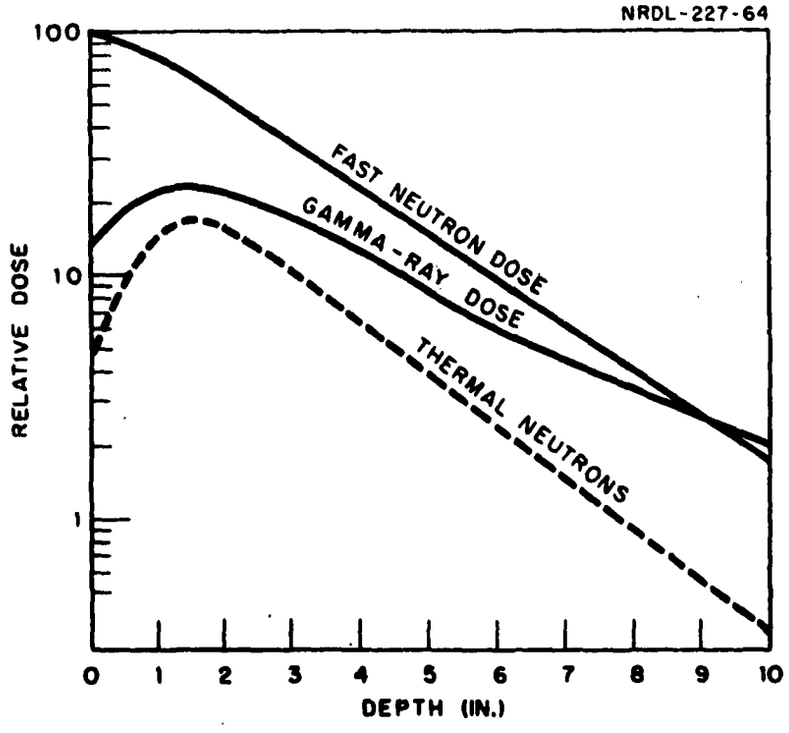


Fig. 4 Penetration of fast neutrons in water (12-MeV protons on thick Be target).

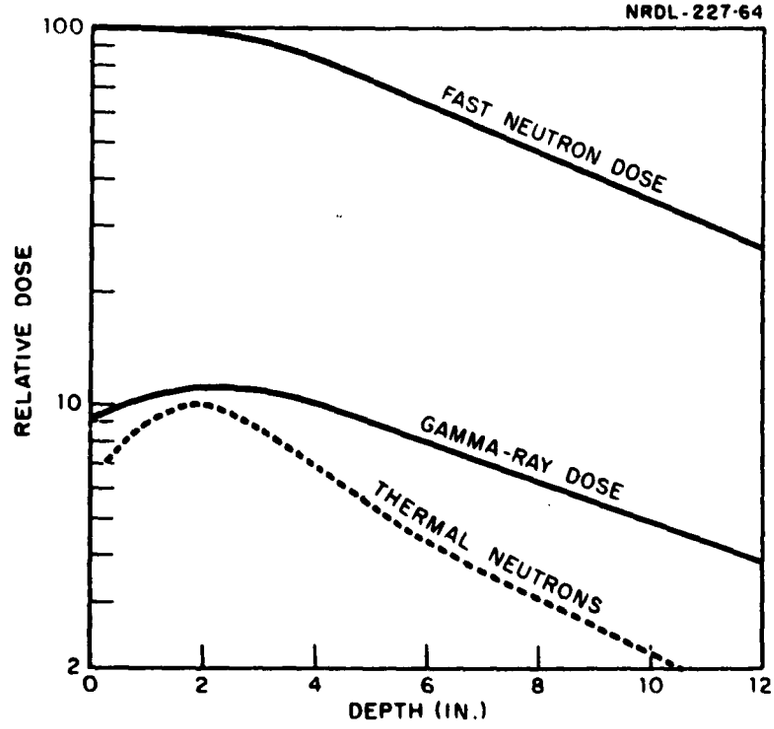


Fig. 5 Penetration of fast neutrons in water (20-MeV deuterons on thick Be target).

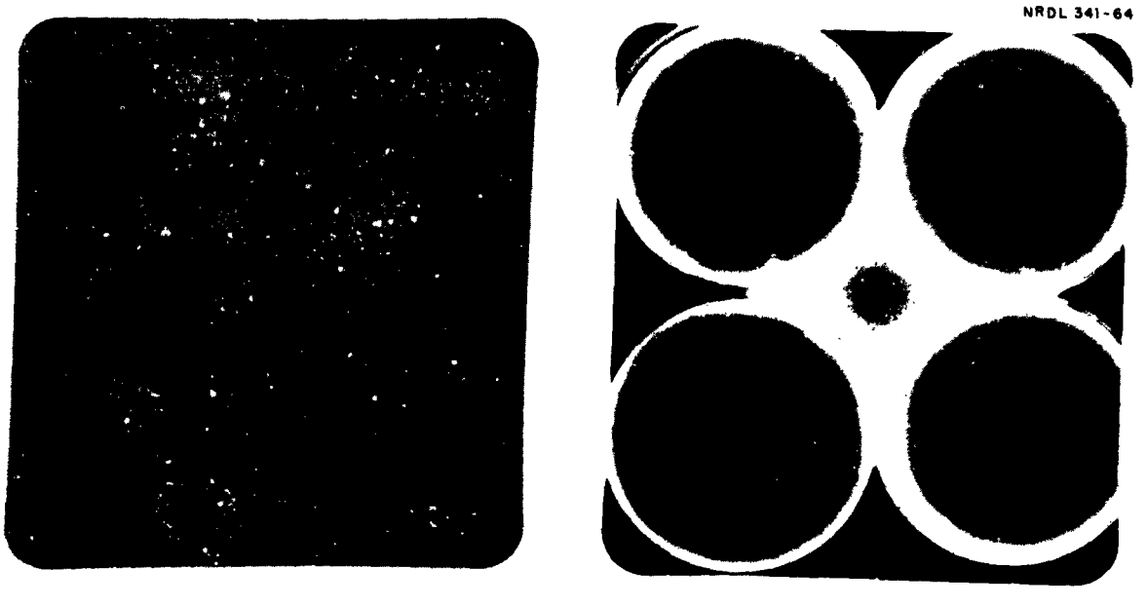


Fig. 6 Neutron radiographs of lead test block.

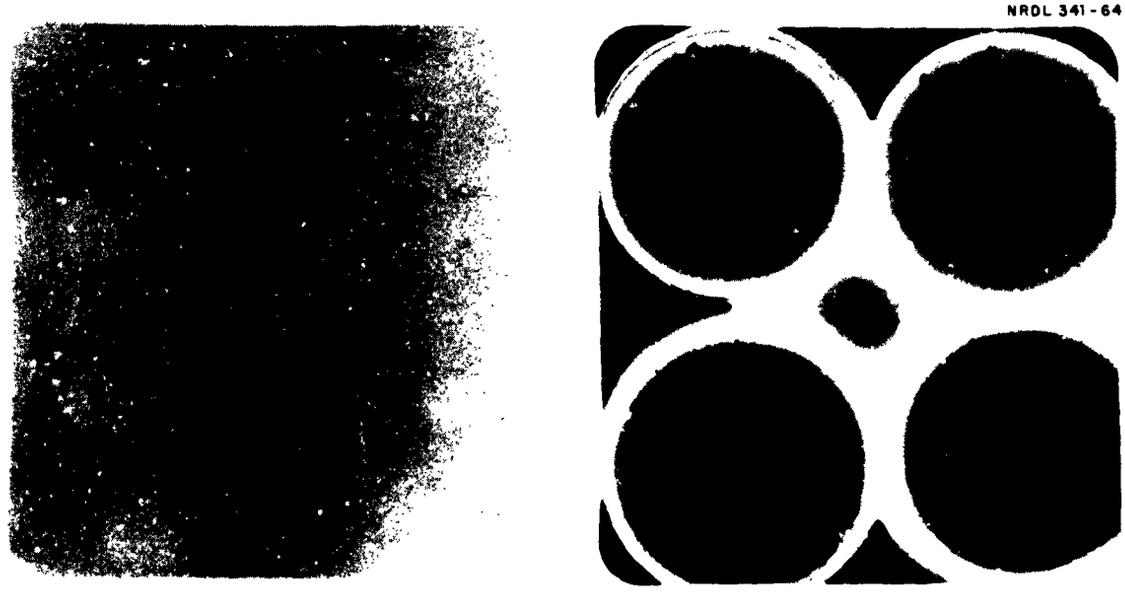


Fig. 7 Neutron radiographs of lead test block behind 2-in. lead absorber.

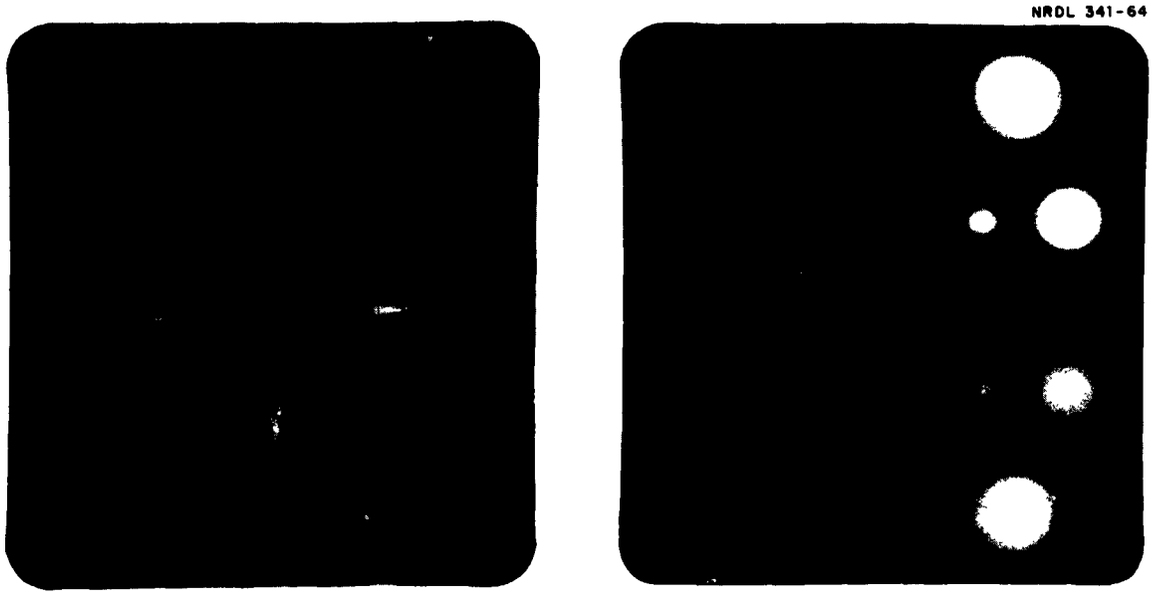


Fig. 8 Co^{60} radiographs of lead test block.

REFERENCES

1. R. J. Smith and R. F. Benck, "Thermal and Fast Neutron Effects on Dosimeter Films," Health Physics 9, 473 (1963).

2. M. Ehrlich, "The Sensitivity of Films to 3 Mev Neutrons and to Thermal Neutrons," Health Physics 4, 113 (1960).

3. E. Tochilin, B. W. Shumway, and G. Kohler, "Response of Photographic Emulsions to Charged Particles and Neutrons," Rad. Res. 4, 467 (1956).

4. A. C. Birge, H. O. Anger, and C. A. Tobias, "Heavy Charged Particle Beams," Radiation Dosimetry, Hine and Brownell, Editors, pages 623-665, Academic Press, Inc., New York (1956).

5. M. Rich and R. Madey, "Range Energy Tables," University of California Radiation Laboratory Report UCRL-2301 (1954).

6. E. Tochilin, et al., "The Dose Response of Glass, Thermoluminescent and Film Dosimeters to High Energy Charged Particles," Rad. Res. 19, 200 (1963).

7. E. Curran, "Luminescence and the Scintillation Counter," Academic Press, Inc., pages 135-147, New York (1953).

8. J. B. Birks, "The Specific Fluorescence of Anthracene and Other Organic Materials," Phys. Rev. 84, 364 (1951).

9. R. B. Murray and A. Mayer, "Scintillation Response of Activated Inorganic Crystals to Various Charged Particles," Phys. Rev. 122, 815 (1961).

10. E. Tochilin and G. Kohler, "Neutron Beam Characteristics from the University of California 60-in. Cyclotron," Health Physics 1, 332 (1958).

11. L. F. Wouters, "The UCRL Plastic Fluor," University of California Radiation Laboratory Report UCRL-4516 (1955).

12. H. Berger, "A Discussion on Neutron Radiography," Non Destructive Testing 20, 185 (1962).

13. H. Berger, "A Comparison of Several Methods for the Photographic Detection of Thermal Neutron Images," J. Appl. Phys. 33, 48 (1962).

14. J. Thewlis, "Neutron Radiography," Brit. J. Appl. Phys. 7, 345 (1956).

INITIAL DISTRIBUTION

Copies	
	NAVY
1	Chief, Bureau of Ships (Codes 320-364A)
2	Chief, Bureau of Ships (Code 210L)
1	Chief of Naval Operations (Op-07T)
1	Chief, Bureau of Medicine and Surgery (Code 74)
3	Director, Naval Research Laboratory
1	Chief of Naval Research (Code 422)
3	CO., Office of Naval Research, FPO, New York
1	Supt. Naval Postgraduate School, Monterey
	ARMY
1	Chief of Research and Development (Atomic Office)
1	Commander, Nuclear Defense Laboratory
1	CO., Army Electronic Res. and Dev. Laboratory
	AIR FORCE
1	Chief, Systems Engineering Group (SEPIR)
1	Director, USAF Project RAND
1	Dir., Air University Library, Maxwell AFB
1	Commander, AF Cambridge Research Laboratories (CRT)
	OTHER DOD ACTIVITIES
3	Dir., Defense Atomic Support Agency (Library)
1	Commander, FC/DASA, Sandia Base (FCTG5, Lib.)
20	Defense Documentation Center
	AEC ACTIVITIES AND OTHERS
3	Argonne National Laboratory
3	Atomic Energy Commission, Washington
2	Battelle Memorial Institute

4	Brookhaven National Laboratory
2	Los Alamos Scientific Lab. (Lib.)
1	NASA, Lewis Research Center
1	National Bureau of Standards (Library)
1	Sandia Corp., Albuquerque
1	Sandia Corp., Livermore
2	U. of California Lawrence Radiation Lab., Livermore
2	U. of California Lawrence Radiation Lab., Berkeley
25	Division of Technical Extension, Oak Ridge

USNRDL

35	Technical Information Division

DISTRIBUTION DATE: 25 August 1964

Naval Radiological Defense Laboratory
USNRDL-TR-766
PHOTOGRAPHIC DETECTION OF FAST NEUTRONS: APPLICATION TO NEUTRON RADIOGRAPHY, by E. Tochilin
21 July 1964 27 p. tables illus. 14 refs.
UNCLASSIFIED

The response of photographic emulsions to fast neutrons has been studied by direct measurements at two neutron energies and by exposure to high-energy charged particles. Dose response was significantly less for neutrons than for gamma rays and decreased progressively with decreasing neutron energy. Increased neutron sensitivity was obtained by use of organic
(over)

1. Fast neutrons.
2. Photographic emulsions.
3. Radiography.

I. Tochilin, E.
II. Title.
III. SF 011 05 11.

UNCLASSIFIED

scintillators as intensifying screens in conjunction with film. Neutron radiographs at two different energies were taken with step wedges made of Al, Cu, Pb and plastic. Radiographs were taken behind 2, 4, 6 and 8 inches of lead. Loss of photographic resolution from gamma rays produced in the test sample and by thermal neutron interactions is discussed.

UNCLASSIFIED

Naval Radiological Defense Laboratory
USNRDL-TR-766
PHOTOGRAPHIC DETECTION OF FAST NEUTRONS: APPLICATION TO NEUTRON RADIOGRAPHY, by E. Tochilin
21 July 1964 27 p. tables illus. 14 refs.
UNCLASSIFIED

The response of photographic emulsions to fast neutrons has been studied by direct measurements at two neutron energies and by exposure to high-energy charged particles. Dose response was significantly less for neutrons than for gamma rays and decreased progressively with decreasing neutron energy. Increased neutron sensitivity was obtained by use of organic
(over)

1. Fast neutrons.
2. Photographic emulsions.
3. Radiography.

I. Tochilin, E.
II. Title.
III. SF 011 05 11.

UNCLASSIFIED

scintillators as intensifying screens in conjunction with film. Neutron radiographs at two different energies were taken with step wedges made of Al, Cu, Pb and plastic. Radiographs were taken behind 2, 4, 6 and 8 inches of lead. Loss of photographic resolution from gamma rays produced in the test sample and by thermal neutron interactions is discussed.

UNCLASSIFIED